Integrated circuits using embedded III-V-on-Ge MHEMTs in multi-layer thin-film technology

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Keywords: MCM-D, Thin-Film Transistor, Semi-Monolithic Integration, MHEMT

Abstract

In this paper a demonstrator oscillator circuit integrated in a MCM-D on glass technology is presented. The active device of the oscillator is a thin-film Ge (germanium) -based MHEMT. The MHEMT is embedded in the bottom dielectric layer of the MCM-D. The combination of passive MCM-D technology and MHEMTs on Ge allows for efficient semi-monolithic integration of active devices and realisation of (optoelectronic) MCMs with embedded passive and active components.

INTRODUCTION

High packaging density and large scale integration of passive and active components have become key issues in the further development of portable communication systems. Good examples of these trends are the upcoming standards for wideband WLANs in the 5-6 GHz band. Earlier developments have shown that MCM-D technology can be a viable candidate for the integration and interconnection of high quality microwave and RF applications [1], [2]. This MCM-D integration of RF (sub-)systems leads to a new implementation paradigm called “System-in-a-Package” (SiP). With this implementation approach, several RF components – each implemented in the most suitable IC technology – can be assembled in a relatively simple and economical way. The passives are as much as possible integrated in the low-cost MCM substrate, hereby reducing the area (and hence the cost) of the active chips.

There are various possibilities to integrate active devices with MCM-D (passive) technology. First, IMEC started with wirebonding GaAs HEMTs on top of a MCM-D carrier substrate. As long wirebonds introduce large parasitic inductances, this method leads to rather poor RF performance. Shifting to flip-chip technology with gold bumps meant shorter interconnect lengths and thus less parasitics and better RF performance. Gold wire studs for thermocompression may be placed at very tight pitches with conventional wirebond equipment [3]. In this paper, a technique for the semi-monolithic integration of an embedded thin-film Ge-based MHEMT in MCM-D, is discussed. Compared to GaAs, Ge is cheap and has a low environmental load. The very thin (< 3 µm) active device is embedded in the MCM-D substrate, together with the passives. In this technique, we use the selective substrate removal method as described in [4]. Due to the dispersive nature of Ge, substrate removal is necessary in order to use these devices in microwave circuits.

MCM-D TECHNOLOGY

Thin-film MCM-Ds are fabricated by a sequential deposition of conductors, typically Cu or Al, and dielectric layers, typically polyimide or BCB, on a substrate base made of ceramic, silicon or metal. When compared to lower-cost MCM-L and MCM-C technologies, MCM-D most closely parallels the processing techniques used in the semiconductor industry [3] and offers higher integration densities.

The IMEC MCM-D technology (Fig. 1 (a)) consists of alternating thin layers of photosensitive BCB (Cyclotene™ from Dow) and low loss Cu metallisations deposited on a borosilicate glass carrier substrate (AF45, $\varepsilon_r = 6.2$). The BCB dielectric has low dielectric losses ($\tan\delta \approx 5.10^{-4}$), a low dielectric constant ($\varepsilon_r = 2.65$) and a low moisture absorption. The material is spin coated in thin films of 5 µm thick, then developed and cured. The curing temperature profile of BCB does not exceed 250 °C, which is significantly lower than for most other dielectric materials, e.g., polyimide. Depending on the required metal thickness, the metal layers are sputtered (Al) and patterned using wet etches or electroplated (Cu) on a thin Ti/Cu seed layer. The 3µm thick Cu metal layer is sandwiched between two 30 nm thick Ti layers rendering good adhesion. The different metal layers are connected through via holes in the BCB dielectric. Due to the photosensitive property of BCB, the vias are immediately formed after the developing step. The via diameter is typically 30 µm.

INTEGRATED PASSIVES

MCM-D is a miniaturisation and integration technology capable of high-frequency and high-quality performance.

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The resistors indicated in Fig. 1 are realised on the lower level, immediately on the carrier substrate [5]. The resistor material is TaN, with typical resistance values of 10-100 Ω per square and temperature coefficients of less than 20-150 ppm per centigrade.

Integrated capacitors may be realised in different ways [4]. The most common type is the classical MIM capacitor. The insulating dielectric may be BCB (capacitance/area ratio ≈ 5.5 pF/mm^2) or anodised tantalum (capacitance/area ratio ≈ 720 pF/mm^2) for large values. For the smallest values (< 100 fF), interdigital realisations may be used.

High quality integrated spiral inductors are hard to realise. Especially on standard silicon, the low resistivity of the silicon causes dielectric losses, hereby limiting the quality of the inductors, integrated in a conventional Al back-end of line, to about 5 at 1 or 2 GHz. When realising the same spiral inductors in MCM-D on a low loss alumina or glass carrier substrate, the quality factor increases tremendously at a lower overall cost [5]. Quality factors above 100 @ 10 GHz (for inductances < 1.7 nH) can be realised. The spiral, integrated in the middle Cu metal layer, is multiturn circular in a coplanar fashion. The center of the spiral is connected to the outside through an overpass using a higher metal layer.

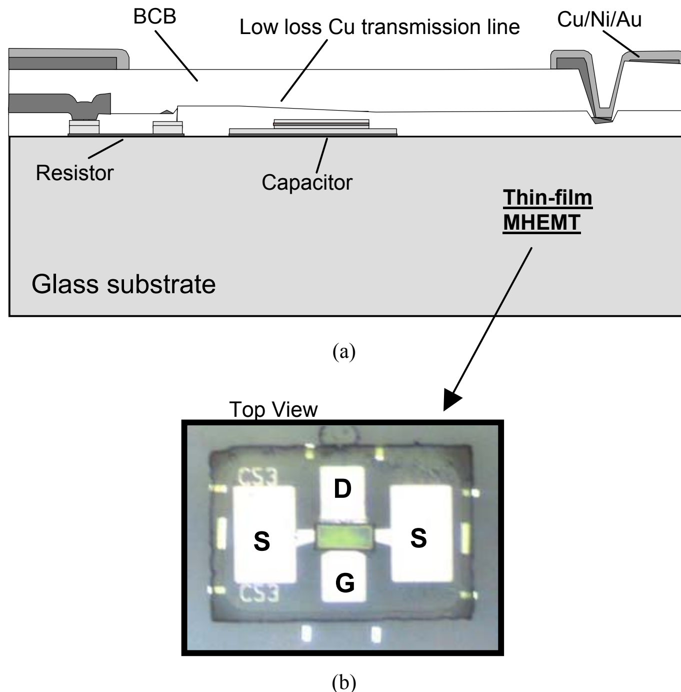

Figure 1: (a) Schematic cross-section of MCM-D structure with integrated passive and active components, (b) top view optical micrograph of a thin-film MHEMT after embedding.

INTEGRATED ACTIVE DEVICES

IMEC's MHEMTs (0.2 µm gate length, 100 µm gate width) are MBE grown and fabricated with the same process as used for the production of InP HEMTs [6]. In the case of MHEMTs on cheap Ge substrates, the conductive nature of the substrate makes such devices unsuitable for microwave applications. The substrate, having served its purpose as a platform for growth, is removed and the MHEMT device is transferred to the glass carrier substrate [4]. The thin-film MHEMTs exhibit excellent DC (g_m = 700 mS/mm) as well as RF (f_T = 80 GHz; f_{max} = 120 GHz) performance.

Prior to the removal of the Ge substrate and after deposition of resistor and capacitor layers on the glass carrier substrate, the Ge wafer is diced. A chip containing a single MHEMT is embedded in a spin coated BCB glue layer using a semi-automated device bonder in thermocompression mode. Chips as small as 400 × 500 µm^2 can be positioned with 3 µm post-bonding accuracy. After glueing the chip in the BCB layer, the polymer needs thermal curing for mechanical strength.

Substrate removal and opening of the contact pads of the thin-film MHEMT are done by a highly selective RIE dry etch, a lithography step for protection of the active area of the transistor and wet etching [4]. It is especially important that this etching method does not damage the previously deposited resistor and capacitor layers. A BCB layer of about 5 µm thick is then spin coated in order to planarise the structure. In order to circumvent problems in the following processing steps, the total thickness of the devices has to be kept below 5 µm. This requirement is easily maintained due to the removal of the substrate and buffer layers. Via holes through the BCB dielectric allow to contact the thin-film transistor. A top view optical micrograph of a thin-film MHEMT on glass is shown in Fig. 1(b). The photograph clearly shows the active area and gold contact pads which are revealed after etching.

Electroplated Cu transmission lines ensure low loss connections to the different passive and active components. Fig.1 shows a cross-section of a complete MCM-D build-up with integrated passive and active devices. A BCB layer covers the entire structure and via holes are made. Finally, Cu/Ni/Au contact pads are deposited.

CIRCUIT DESIGN AND MEASUREMENT RESULTS

To demonstrate the abilities of this combination of passive MCM-D technology and thin-film MHEMTs based on Ge, an integrated circuit has been designed and realised. As demonstrator we chose an oscillator centered around a frequency of about 7.5 GHz. The circuit has been designed using a measurement-based small-signal equivalent model of the thin-film MHEMT and IMEC's integrated passives

design library containing parameterised scalable models [7]. The component library is integrated in Agilent's ADS CAE environment. This allows easy and accurate co-design of the active and passive devices. Fig. 2. shows the measured S-parameters for a MHEMT on a combined Smith chart/polar plot. The influence of the dispersive Ge substrate on the S-parameters has completely disappeared after substrate removal.

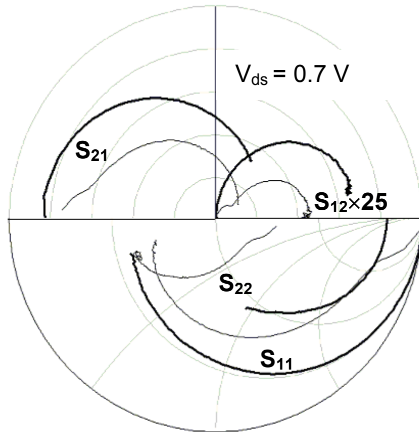

Figure 2: Measured S-parameters for a MHEMT based on a Ge substrate (Combined Smith chart/polar plot; before (thin) and after (thick) substrate removal; 100 MHz – 50 GHz, 201 points).

CPW transmission lines (realised on the middle 3 μm thick Cu layer, Fig. 1(a)) are used as this has several advantages over the more traditional microstrip approach: through-substrate vias are not required and backside wafer processing can be omitted.

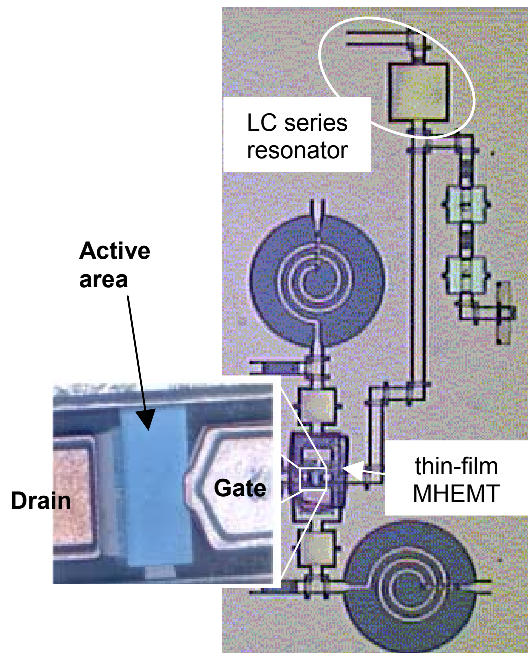

Figure 3: Top view optical micrograph of the MCM-D circuit.

The circuit layout consists of one embedded transistor and a series LC resonator at the gate of the transistor. At the source, the transistor is destabilised by a MIM capacitor-to-ground. In order to reduce the surface area, the inductor in the resonator is replaced by a transmission line. Also in the DC bias network, resistors have been used instead of spiral inductors since no current has to be delivered to the gate of the transistor.

All active and passive elements are embedded in the MCM-D substrate. An external bias-tee is used for biasing the drain of the transistor. Fig. 3 shows a picture of the circuit.

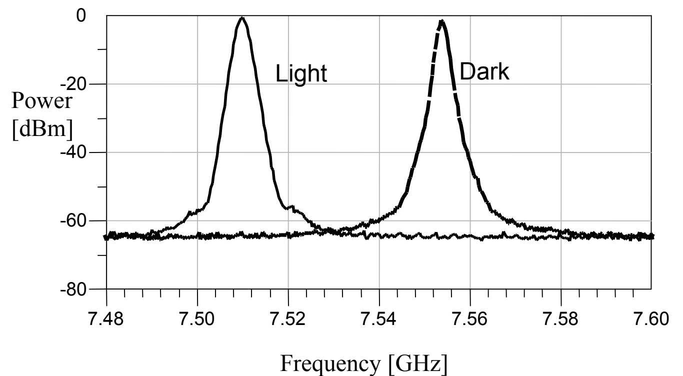

Figure 4: Oscillator output spectrum at the fundamental oscillation frequency and optical tuning range.

The output power of the oscillator is about 0 dBm. Fig. 4 shows the power spectrum of the oscillator in dark and under illumination of the transistor. The light source is a standard telecom laser emitting at a wavelength of 1550 nm. The optical output power of the laser is 10 mW. A single-mode fiber pigtail is connected to a lightwave probe in order to provide precise illumination of the active region of the transistor [8]. Efficient light coupling into the thin-film transistor allows for an optical tuning range of 43 MHz. Light is absorbed in the active $In_{.53}Ga_{.47}As$ channel layer. The main reason for the decrease in oscillation frequency is the increase in gate-to-source capacitance of the transistor due to light [9], [10].

This demonstrates the optical characteristics of the thin-film MHEMT and the optical tuning of the MCM-D oscillator. It also shows that this integration technique is well-suited for opto-electronic circuits, e.g., optically tunable oscillators and direct optical injection locked oscillators.

CONCLUSIONS

Thin-film multilayer MCM-D technology using the SiP concept is presented as a viable approach for the integration of high performance passives and embedded active devices.

The embedded thin-film active devices are MHEMTs based on low-cost Ge substrates.

An oscillator integrated circuit has been fabricated to demonstrate the abilities of the combination of MCM-D and III-V-on-Ge technology.

ACKNOWLEDGEMENTS

The authors would like to thank P. Mijlemans (Umicore) for supply of Ge wafers and R. Van Hoof and J. Hendrickx for MCM-D processing. Additionally, financial support from IWT and FWO Flanders was appreciated.

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ACRONYMS

MHEMT: Metamorphic High Electron Mobility Transistor
MCM-D: Multi-Chip Module with Deposition of thin-film layers
WLAN: Wireless Local Area Network
SiP: System-in-a-Package
MCM-L: Multi-Chip Module with organic Laminate layers
MCM-C: Multi-Chip Module with Ceramic layers
BCB: BenzoCycloButene
MBE: Molecular Beam Epitaxy
RIE: Reactive Ion Etching
ADS: Advanced Design System
CAE: Computer Aided Engineering
MIM: Metal-Insulator-Metal
LC: Inductor Capacitor
CPW: Coplanar Waveguide

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